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PIEZOELECTRIC NON-LINEAR NANOMECHANICAL TEMPERATURE AND ACCELERATION INSENSITIVE CLOCKS (PENNTAC)

Phase I Evaluation and Plans for Phase II

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During Phase I, the primary objective of the PENNTAC team has been to understand the non-linear dynamics of laterally vibrating aluminum nitride resonators and harness the bifurcation phenomenon in an electronic ascillatro to meet the – 90 dBc/Hz at 1 kHz offset requirement. By exploiting non-linear dynamics, we were able to even exceed the phase noise metrics at 1 kHz offset (-94 dBc/Hz) for 1 GHz carrier and reduce the noise floor to levels < - 170 dBc/Hz. The use of non-linear dynamics resulted in a net phase noise improvement with respect to the linear case of more than 7 dBc/Hz at 1 kHz offset, and > 20 dBc/Hz at offsets greater than 10 NHz.

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PiezoElectric Non-linear Nanomechanical Temperature and Acceleration insensitive Clocks (PENNTAC)

PHASE I EVALUATION and PLANS for PHASE II

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PHASE I ACCOMPLISHMENTS

Harnessing Non-Linear Dynamics to Lower Phase Noise in 500 MHz to 1 GHz Oscillators

During Phase I, the primary objective of the PENNTAC team has been to understand the non-linear dynamics of laterally vibrating aluminum nitride resonators and harness the bifurcation phenomenon in an electronic oscillator to meet the – 90 dBc/Hz at 1 kHz offset requirement. By exploiting non-linear dynamics, we were able to even exceed the phase noise metrics at 1 kHz offset (- 94 dBc/Hz) for 1 GHz carrier and reduce the noise floor to levels < - 170 dBc/Hz (Fig. 1). The use of non-linear dynamics resulted in a net phase noise improvement with respect to the linear case of more than 7 dBc/Hz at 1 kHz offset, and > 20 dBc/Hz at offsets greater than 10 MHz. To our knowledge, this is the best performing 1 GHz miniaturized oscillator ever demonstrated. The same experimental response was attained in different oscillator topologies and transistor technologies (CMOS, GaAs, SiGe), therefore confirming that this advantage is coming from the non-linear dynamics of the resonant device.

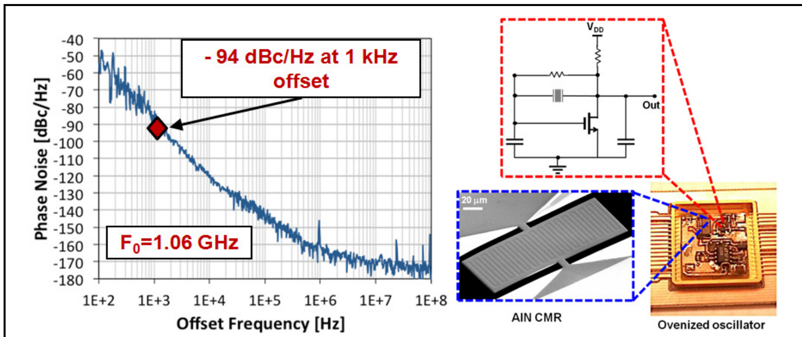

Fig.1: Phase noise performance for a 1.06 GHz Pierce oscillator using an AlN resonator (see SEM picture) and a GaAs amplifier (see packaged unit). This 1 GHz oscillator meets the program phase noise specifications at 1 kHz offset, but also attains a phase noise floor level (< -170 dBc/Hz), which translates to ultra low jitter and improved radio communication range.

In terms of AlN resonator ***non-linear dynamics*** we have made the following discoveries:

- For slowly varying modulation of power (or current being the controlling parameter of the bifurcation), the resonator non-linearity is dominated by thermal effects due to self-heating. The thermal non-linearities are governed by the dependence of the AlN Young's modulus on temperature, the thermal and electrical resistance of the device and its frequency of operation (see Fig. 2 for equation). This was confirmed by monitoring the device temperature in-situ via an integrated serpentine heater and by means of direct measurement of bifurcation via a high speed optical interferometer.
- For fast variations in power (> 10 kHz) the resonator non-linearity are dominated by mechanical effects and related to softening of the material with the level of internal strain. Since it occurs for fast variations of the control variable (and for which the thermal response is heavily attenuated), this mechanical non-linearity has limited impact on the phase noise of the oscillators constructed with the AlN resonators.

We have fit the non-linear behavior of the AlN resonators via a third-order coefficient and developed a lumped electromechanical model that is used to describe the device behavior in an electronic circuit such as an oscillator (Fig. 2). This third-order coefficient has also been used to develop a multiphysics model that accurately incorporates both thermal and mechanical nonlinearities and allows us to simultaneously observe the mechanical and electrical characteristics of the driven oscillator.

The operation of the resonator in the non-linear regime results in a phase-frequency response that

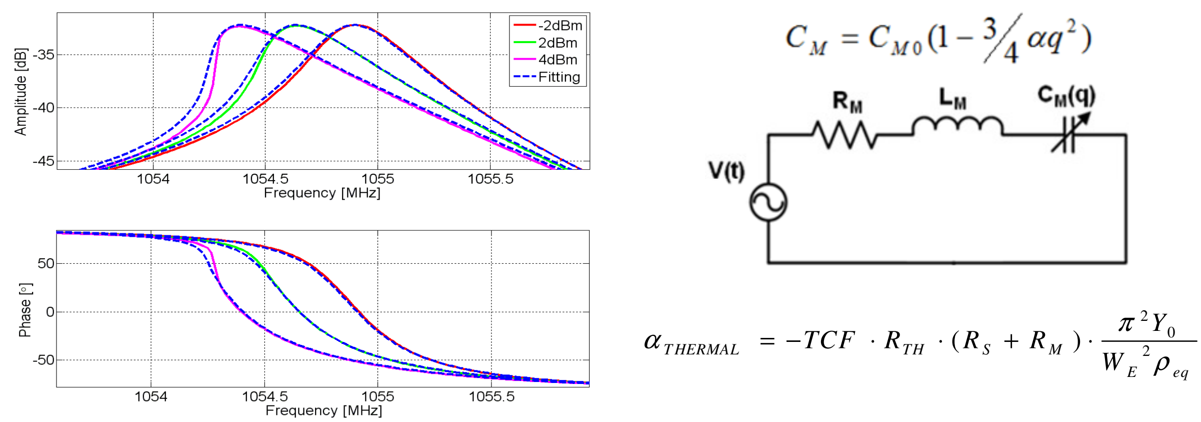

Fig.2: Amplitude-frequency measurements and fitting of the AlN resonator response in the non-linear regime. The main source of the recorded duffing behavior is the thermal modulation of the AlN Young's modulus due to self-heating. An equivalent electrical model was produced. The non-linear coefficient, α, was also derived analytically and shows a dependence on the thermal, R_{TH}, and electrical (R_S+R_M) resistance of the device. Y_o is the Young's modulus of AlN, ρ_{eq} is the equivalent mass density of the resonator, and W_E is the width of each of the fingers composing the resonator.

exhibits an increasing slope as bifurcation is approached. Operating in proximity of this bifurcation was positively exploited to shift the pole that controls the feedback loop of the oscillator (the closed-loop configuration) towards zero, and effectively reducing the thermomechanical and flicker noise contribution from the circuit and the resonator. Nonetheless, operating close to or past bifurcation results in an additional noise term due to the conversion of amplitude modulation (due to the large non-linear drive) into frequency and therefore phase fluctuations. Therefore, an optimal region of operation (controlled by the current into the resonator) exists. To identify this point of operation we have modified the classical linear Lesson's equation for phase noise to include the effect of non-linear dynamics. The phase noise, *L(f),* in the non-linear regime can be expressed via the equation reported below:

$$L(f) = S_{\Phi n}(f)\left[1 + \left(\frac{d\Phi}{df}\right)^{-2}\left(\frac{1}{f}\right)^{2}\right] + S_{fn}(f)\frac{1}{f^2} \qquad (1)$$

$$S_{\Phi n}(f) = \frac{kT}{P_0} + \frac{FkT}{P_0} + \frac{\alpha}{f}\frac{1}{P_0}$$

$$S_{fn}(f) = \left|\frac{df}{di}\right|^2 S_{in}(f) = \left|\frac{df}{di}\right|^2 \left(\frac{2kT(1+F) + {}^{2\alpha}\!/_f}{R_M}\right) = \left|\frac{df}{di}\right|^2 i^2 \left[\frac{kT(1+F) + \frac{\alpha}{f}}{P_0}\right] = \left|\frac{df}{di}\right|^2 i^2 S_{\Phi n}(f)$$

Where k is the Boltzmann's constant, T the temperature of operation, P_o the power injected in the resonator, f the offset frequency from the carrier, F the noise figure of the amplifier, α the flicker noise of the system and R_M is the motional impedance of the resonator.

Two main terms are important in describing phase noise in the non-linear regime:

- The inverse of the derivative of the phase with respect to frequency, *dΦ/df*, which replaces the classical linear pole defined as $f_o/2Q$ (where f_o is the carrier frequency and Q is the quality factor of the resonator). The inverse of this slope is equal to $f_o/2Q$ in the linear regime, but tends to zero as we approach bifurcation in the non-linear regime. As shown in Eq. 1, this effect is advantageous in reducing or eliminating the classical contribution coming from thermomechanical and flicker noise.

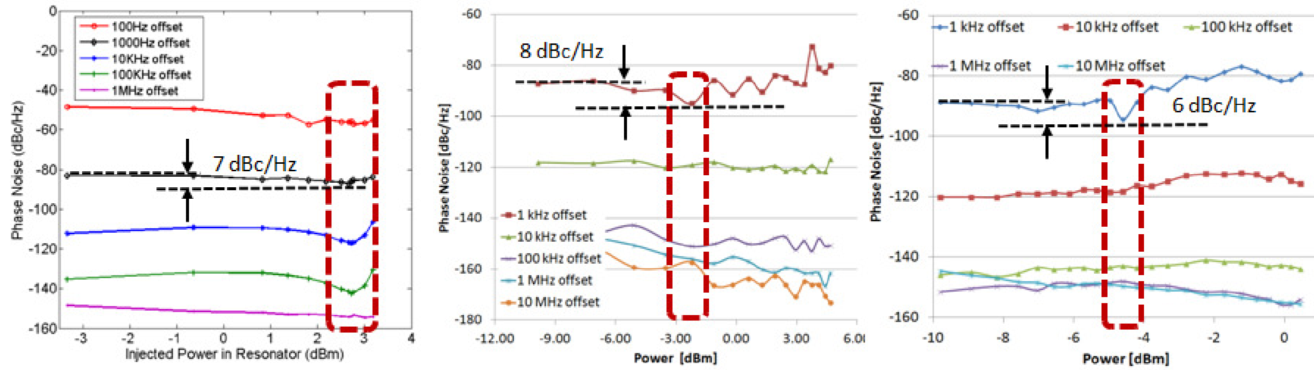

Fig .3: (a) Phase noise for different offset frequencies and power into the resonator for a CMOS series oscillator built with a 1 GHz AlN resonator. (b) Phase noise for different offset frequencies and power into the resonator for a SiGe Pierce oscillator built with a 545 MHz AlN resonator. (c) Phase noise for different offset frequencies and power into the resonator for a GaAs Pierce oscillator built with a 582 MHz AlN resonator. Note that in all 3 cases a minimum of the phase noise at 1 kHz offset exists. This point corresponds to an amount of power close to the level of bifurcation in the open-loop measurement of the resonator. Also note that at 1 kHz offset, non-linear dynamics enables 7 dB improvement in (a), 8 dB improvement in (b), and 6 dB improvement in (c) with respect to a purely linear operation. The phase noise value at 1 kHz offset are respectively: (a) – 89.5 dBc/Hz, (b) – 95.2 dBc/Hz, (c) - 94.2 dBc/Hz.

- The introduction of an amplitude-frequency term (*df/di*), which describes how the frequency variations induced by changes in mechanical deformations translate to additional phase noise in the non-linear regime. The value of this derivative depends on the non-linear coefficient, α, and the square of the current driving the resonator. This phenomenon counteracts the positive action of bifurcation-induced reduction of the intensity of thermomechanical and flicker noise, therefore resulting in an optimal point of operation controlled by the input current into the resonator.

Minimization of the phase noise described by Eq. 1 at a specific offset corresponds to a power level (input current into the resonator) approximately approaching the bifurcation of the device in the open-loop configuration. We have verified this theoretical prediction experimentally both in the case of series resonance and Pierce oscillators at frequencies varying between 500 MHz and 1 GHz (see Fig. 3a-c).

The demonstrated oscillators at 1 GHz in CMOS (Fig. 3a), 545 MHz in SiGe (Fig. 3b) and 582 MHz (Fig. 3c) in GaAs attained phase noise performance at 1 kHz offset that meets the specification of Phase I, being respectively, -89.5 dBc/Hz, - 95.2 dBc/Hz, and – 94.2 dBc/Hz. The 582 MHz oscillator was also packaged and tested for temperature and acceleration sensitivity.

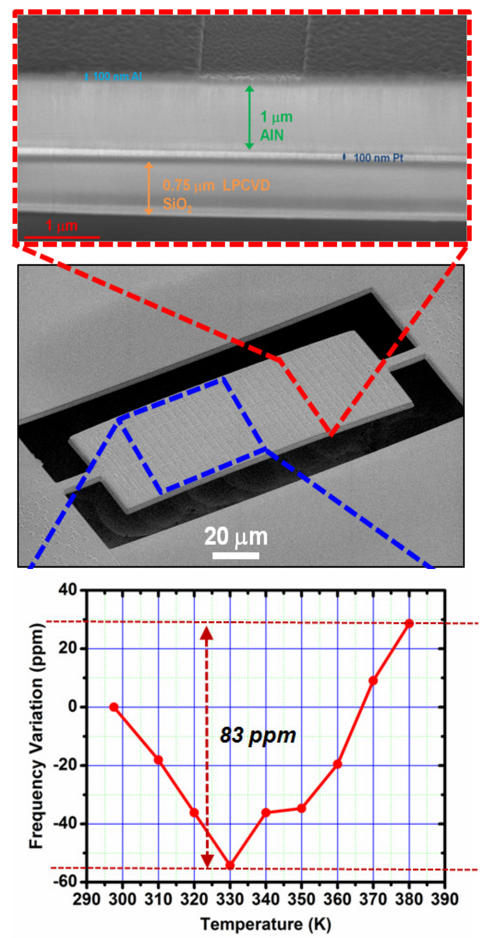

Fig. 4: Mechanically compensated AlN resonators. A thin oxide layer is used to completely cancel the linear TCF of the resonator. The resonator was tested between 25 and 85 °C and exhibited a total TC of 83 ppm.

Temperature Compensation

The uncompensated AlN resonator exhibits a linear dependence of frequency on temperature and has a corresponding temperature coefficient of frequency (TCF) of ~ - 28 ppm/K. This means that the oscillator will exhibit a minimum shift of 3500 ppm when operated between – 40 and + 85 °C. In order to significantly reduce the temperature sensitivity of the resonator we have worked on a twofold approach:

- Mechanical compensation of the softening of the AlN Young's modulus by including a thin layer of SiO_2 (~ 700 nm for 1 μm thick AlN) into the resonator stack. As shown by the experimental results in Fig. 4, we were able to completely eliminate the linear TCF of the resonator and obtain a total variation of 83 ppm between 25 and 85 °C.
- Ovenize the mechanical resonator by embedding a serpentine heater into the body of the resonator (Fig. 5). The serpentine acts simultaneously as a heater and temperature sensor, which can be used to monitor temperature variations in the environment and consequently keep the resonator at a constant temperature (note that to satisfy Phase I requirements a 1 °C control is needed). The resonator can be heated to about 100 °C (above the max operating temperature of + 85 °C) by few mW of power.

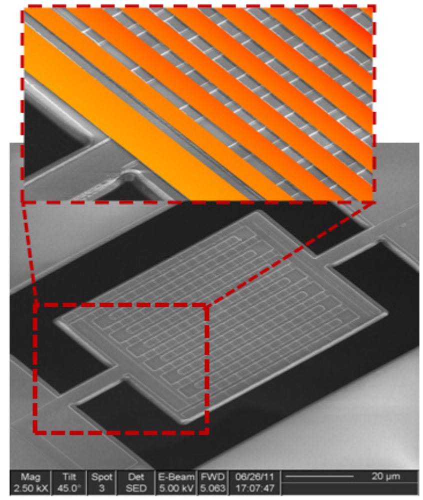

Fig. 5: Serpentine heater embedded in the body of the resonator. The serpentine is used simultaneously as a heater and temperature sensor.

For the purpose of meeting Phase I requirements we have focused on the 2nd approach. A combined approach based on mechanical compensation and ovenization will be explored to meet the more stringent requirements of Phase II and III. A simple controller was used to ovenize the oscillator. The circuit to drive the oven is formed by a Wheatstone bridge, and a differential amplifier that senses the temperature variations and controls the current flowing into the heater so as to keep the resonator at a constant temperature. The Wheatstone bridge resistors and bias voltage were selected so as to guarantee operation at a desired temperature above the maximum external ambient temperature. A 582 MHz ovenized oscillator was packaged (Fig. 6) with the control circuit and tested for frequency and phase noise variations from – 40 to + 85 °C. The collected data for the frequency shift are shown in Fig. 7. The oscillator exhibits a total frequency shift over temperature < 130 ppm, which corresponds to approximately a 30X improvement with respect to the uncompensated case. Through various experiments, we have confirmed that the frequency shift occurring at low temperature is not due to the mechanical resonator, but the electronic oscillator. By monitoring the ambient temperature and controlling the value of one resistance in the Wheatstone bridge, we were able to tune the temperature set point of the resonator, so as to compensate for the shift produced by the electronic

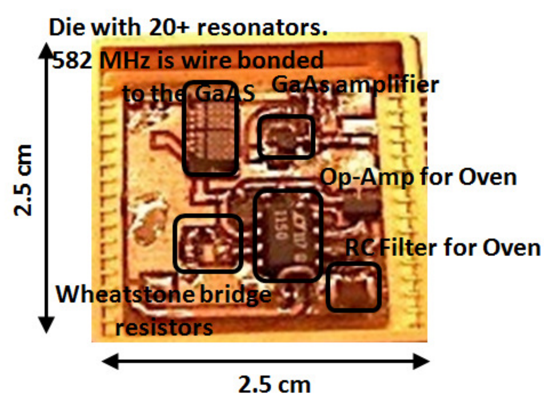

Fig. 6: Fully packaged 582 MHz oscillator based on an AlN resonator and GaAs amplifier. The Wheatstone bridge and controlling amplifier are also mounted on the same board and placed inside the package.

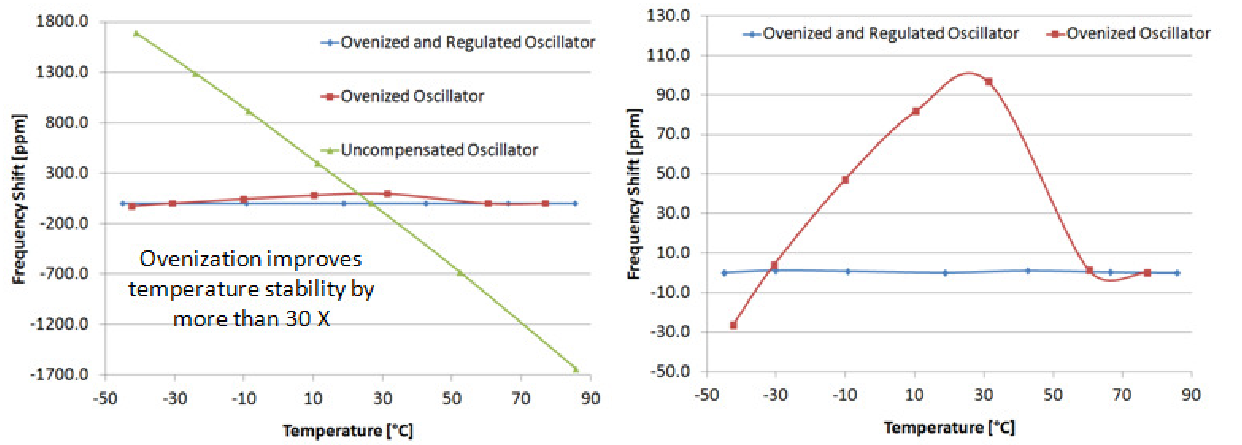

Fig. 7: Frequency shift over temperature (-40 to + 85 °C) of the ovenized 582 MHz unit of Fig. 6. Three curves are shown to highlight the more than 30 X improvement in frequency shift that we attained by going from the uncompensated case (oven off and 3500 ppm of shift), to the cases with the oven on (130 ppm), and the oven on with additional control of the Wheatstone bridge (< 2 ppm). A zoomed in view of the frequency shift in the ovenized and ovenized + Wheatstone bridge control oscillators are also shown for clarity.

components. The collected data with the additional control of the Wheatstone bridge resistance are shown in Fig. 7. In this case, a total frequency shift < 2 ppm is recorded. <u>*This data confirms that the ovenization approach in conjunction with additional electronic control of the Wheatstone bridge set point meets the Phase I program goal of attaining an oscillator with a temperature coefficient lower than 30 ppm.*</u>

Acceleration Sensitivity

Although a miniaturized and ultra-stiff device in the GHz range, the laterally vibrating AlN resonator effectively looks like a flexural plate at low mechanical frequencies (100 Hz to 10s of kHz). Because of this, it could be subject to large displacements in the out-of-plane direction (z-direction) when an external acceleration is applied to it. COMSOL finite element simulations of the AlN resonator under acceleration in various directions were conducted and showed that the shift in frequency with acceleration is generally well below the program requirements and < 0.5 ppb/G. Therefore, we have conducted direct experiments on the same 582 MHz unit packaged with the oven controller. The preliminary results collected at Vectron are shown in Fig. 8. The experimental data are likely affected by the poor cabling and connections between the PCB and the package. Fig. 8 compares the data for two similar 582 MHz units, but for which two different kinds of adhesive bonding between the PCB and the package were used. The stronger adhesive (epoxy) shows better performance. Although far from the intrinsic device limit, the ovenized unit showed an acceleration sensitivity below 40 ppb/G, therefore meeting the Phase I requirements.

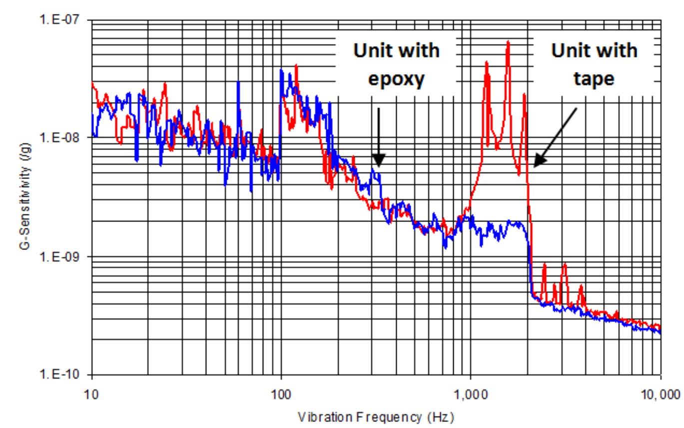

Fig. 8: Acceleration sensitivity testing performed at Vectron on two 582 MHz units such as the one in Fig. 6 and that were previously tested for temperature sensitivity. The difference in performance appears to be affected by the way the PCB is attached to the package. Likely cabling, wiring and die attachment are also other sources of acceleration sensitivity. The unit with epoxy shows acceleration sensitivity < 40 ppb/G.

Summary of Phase I Accomplishments Compared to Program Milestones for 1 of the PENNTAC Units

	Frequency [MHz]	Phase Noise at 1 GHz for 1 kHz offset [dBc/Hz]	Acceleration Sensitivity [ppm/G]	Temperature Coefficient [ppm]
PHASE I METRIC	**500**	**- 90**	**10**	**30**
582 MHz PENNTAC UNIT	**582**	**- 89.6**	**0.04**	**2**

PHASE II PLANS

Phase II goals are listed below:

	Frequency [MHz]	Phase Noise at 1 GHz for 1 kHz offset [dBc/Hz]	Acceleration Sensitivity [ppm/G]	Temperature Coefficient [ppm]	Volume [mm^3]
PHASE II METRIC	**800**	**- 110**	**0.1**	**10**	**30**

Briefly, in the following sections we outline our approach and risk mitigation for each metric.

Frequency

This is a very low risk goal for our team. We have already demonstrated resonator and oscillators operating up to 1 GHz. We can control the resonator geometry and fabrication to produce AlN resonators operating at 800 MHz. We are also familiar with the required electronics to design the electronic oscillator at this frequency.

Phase Noise

Our team believes that this is the highest risk task for Phase II. We will focus our research efforts on further harnessing non-linear dynamics to shape the phase noise of the oscillator and meet the specifications. According to our analysis, the phase noise performance of our Phase I oscillator is limited by the close-in flicker noise (1/f transformed into $1/f^3$ by the feedback loop) coming from the sustaining circuit. We believe that by exploiting parametric oscillation (Fig. 9), we will obtain sufficient gain conversion to drive the resonator via the non-linear element. In this way, the 1/f noise coming from the amplifier will be

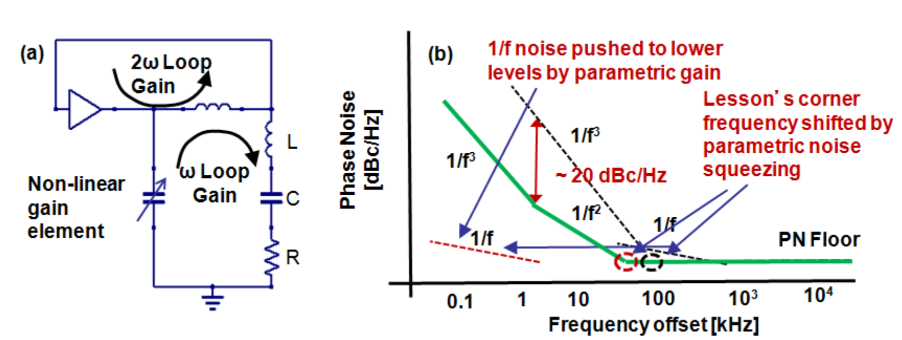

Fig. 9: (a) Schematic representation of a non-linear parametric oscillator. In this case, the non-linear component that is parametrically pumped is represented by a non-linear capacitor. This capacitor will be first implemented via a varactor and then substituted by a purely mechanical component. (b) The use of parametric oscillation is expected to reduce the 1/f noise and also provide additional noise squeezing. These two combined effects will yield better than 20 dBc/Hz noise reduction therefore enabling us to meet the Phase II specifications.

eliminated or significantly reduced and pushed to a lower corner frequency. This is based on the assumption, as proven by our current experiments, that the non-linear mechanical element will have a lower 1/f noise than the amplifier. We will use an incremental approach to demonstrate the advantages of a parametric oscillator: (i) we will first use an external electronic varactor to prove that a parametric oscillator can be designed and the 1/f noise magnitude lowered; (ii) we will then move to an on-chip realization of a mechanical varactor and (iii) finally integrate the parametric functionality into the same AlN resonator. We expect to attain the ultimate phase noise performance from this approach. The elimination or downshift in frequency of the 1/f noise will result in ~ 20 dBc/Hz gain in phase noise performance (Fig. 9), therefore permitting us to meet the desired metric of – 110 dBc/Hz at 1 kHz offset.

Acceleration Sensitivity

This is a very low risk task. Our Phase I oscillator already meets the Phase II goals. We will further investigate the device acceleration sensitivity and identify the main reasons why the experimental results are deviating from the COMSOL FEM analysis. We expect to be able to get close to the FEM prediction (therefore exceeding Phase III goals). We suspect that the primary sources of acceleration sensitivity are coming from cabling and packaging. We will monitor the major sources of vibration sensitivity in the oscillators and devise methods to properly package them so as to attain the ultimate acceleration sensitivity specifications.

Temperature Coefficient

This is considered a medium risk task. Leveraging the knowledge acquired in Phase I, we will use a hybrid approach to meet the more stringent Phase II goals. We will combine mechanical compensation with an ovenized solution. In this case (Fig. 10) we will place the oven outside the body of the resonator to avoid further reducing the electromechanical coupling coefficient of the oxide-based device. The use of a mechanical compensated resonator relaxes the degree of control required on the oven, therefore making it possible to meet the more stringent requirements of Phase II with the simple electronic circuit demonstrated in Phase I.

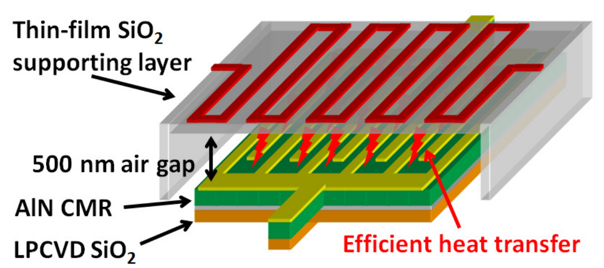

Fig. 10: Schematic representation of the envisioned ovenized and mechanically compensated resonator structure that will be used to meet the temperature stability goals of phase II. By decoupling the mechanical compensation from the ovenization process we will preserve the same electromechanical property of the resonator and attain a very high level of control of the resonator temperature.

Volume

We consider the volume specification to be relatively low risk. The current volume of the 582 MHz is about 1,200 mm^3 and is limited by the use of an off-the-shelf operational amplifier for the temperature controller, external resistors for the Wheatstone bridge and non-singulated resonator dies (more than 20 resonators are contained in the existing die). We plan to include the control circuit for the oven on the CMOS die of the oscillator circuit. We also plan to integrate the resistors of the Wheatstone bridge onto the resonator die. We expect our new packaged solution to occupy a volume lower than the required 30 mm^3.